SYSTEM AND METHOD FOR MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) RADIO COMMUNICATION

This application claims priority to U.S. Provisional Application No. 60/319,437, filed July 30, 2002, to U.S. Provisional Application No. 60/461,672, filed April 10, 2003, and to U.S. Provisional Application No. 60/479,945, filed June 19, 2003. The entirety of each of these applications is incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention is directed to a system and method to maximize capacity and/or range of a wireless radio communication link between two radio communication devices.

Multiple-input multiple-output (MIMO) radio communication techniques are known to enhance the received SNR for signals transmitted by one device to another. Research in MIMO radio algorithms has been conducted in which multiple signal streams are transmitted simultaneously from multiple antennas at one device to another device, thereby greatly enhancing the data rate of the wireless radio channel between two devices. One prior approach for transmitting multiple signals streams simultaneously by a plurality of antennas uses a power constraint on the total power transmitted by the plurality of antennas combined and a waterfilling solution. The waterfilling solution requires multiple full-power power amplifiers at the transmitting device since, for some channels, it is possible that all or nearly all the transmit power may be transmitted from one power amplifier. There is room for improving the design of devices capable of MIMO radio communication, particularly where it is desirable to fabricate the radio transceiver of the device in an integrated circuit.

SUMMARY OF THE INVENTION

Briefly, a system, method and device are provided for simultaneous radio communication of multiple signals (signal streams) between a first device having N plurality of antennas and a second device having M plurality of antennas. Unlike prior approaches, the approach taken herein is to impose a power constraint on each transmit antenna path at the transmitting device.

At the first device, a vector **s** representing L plurality of signals $[s_1 \ldots s_L]$ to be transmitted are processed with a transmit matrix **A** to maximize capacity of the channel between the first device and the second device subject to a power constraint that the power emitted by each of the N antennas is less than or equal to a maximum power. The power constraint for each antenna may be the same for all antennas or specific or different for each antenna. For example, the power constraint for each antenna may be equal to a total maximum power emitted by all of the N antennas combined divided by N. The transmit matrix **A** distributes the L plurality of signals $[s_1 \ldots s_L]$ among the N plurality of antennas for simultaneous transmission to the second device. At the second device, the signals received by the M plurality of antennas are processed with receive weights and the resulting signals are combined to recover the L plurality of signals. Solutions are provided for the cases when $N > M$ and when $N \leq M$.

The performance of a system in which the communication devices are designed around a power constraint at each antenna is nearly as good as the optimal waterfilling solution, yet provides significant implementation advantages. The radio transmitter can be implemented with power amplifiers that require lower power output capability, and thus less silicon area. Consequently, there is lower DC current drain by the transmitter, and lower on-chip interference caused by the power amplifiers.

The above and other objects and advantages will become more readily apparent when reference is made to the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a system diagram showing two multiple-antenna radio communication devices, where multiple signal streams are simultaneously transmitted from a first device to a second device.

FIG. 2 is a flow chart depicting the mapping and multiplexing of signals to multiple antenna paths for simultaneous transmission.

FIG. 3 is a block diagram of a radio communication device capable of performing the MIMO radio communication techniques shown in FIG. 1.

FIG. 4 is a block diagram of an exemplary transmitter section of a modem forming part of the device shown in FIG. 3.

FIG. 5 is a block diagram of an exemplary receiver section of the modem.

FIG. 6 is a graphical plot that illustrates the relative performance of the MIMO radio techniques described herein.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to FIGs. 1 and 2, a system 10 is shown in which a first radio communication device 100 having N antennas 110(1) to 110(N) communicates by a wireless radio link with a second communication device 200 having M antennas 210(1) to 210(M). In the explanation that follows, the first communication device transmits to the second communication device, but the same analysis applies to a transmission from the second communication device to the first. The multiple-input multiple-output (MIMO) channel response from the N antennas of the first communication device to the M antennas of the second communication device is described by the channel response matrix **H**. The channel matrix in the opposite direction is $\mathbf{H}^T$.

Device 100 will simultaneously transmit L plurality of signals $s_1, s_2, \ldots, s_L$ by antennas 110(1) to 110(N). A vector **s** is defined that represents the L plurality of signals $[s_1 \ldots s_L]$ (at baseband) to be transmitted such that $\mathbf{s} = [s_1 \ldots s_L]^T$. The number (L) of signals that can be simultaneously transmitted depends on the channel **H** between device 100 and device 200, and in particular $L \leq$ Rank of $\mathbf{H}^H\mathbf{H} \leq \min(N,M)$. For example, if $N = 4$, and $M = 2$, then $L \leq$ Rank of $\mathbf{H}^H\mathbf{H} \leq 2$.

The device 100 has knowledge of the channel state (e.g., using training sequences, feedback, etc.), i.e., device 100 knows **H**. Techniques to obtain and update knowledge of the channel **H** at the transmitting device (between the transmitting device and a receiving device) are known in the art and therefore are not described herein. For example, training and feedback techniques are described in U.S. Patent No. 6,144,711 to Raleigh et al.

Two matrices are introduced: **V** is the eigenvector matrix for $\mathbf{H}^H\mathbf{H}$ and $\mathbf{\Lambda}$ is the eigenvalue matrix for $\mathbf{H}^H\mathbf{H}$. Device 100 transmits the product $\mathbf{As}$, where the matrix **A** is the spatial multiplexing transmit matrix, where $\mathbf{A} = \mathbf{VD}$. The matrix $\mathbf{D} = \text{diag}(d_1,\ldots,d_L)$

where $|d_p|^2$ is the transmit power in p^{th} mode, or in other words, the power of the p^{th} one of the L signals. Device 200 receives $\mathbf{HAs} + \mathbf{n}$, and after maximal ratio combining for each of the modes, device 200 computes $\mathbf{c} = \mathbf{A}^H\mathbf{H}^H\mathbf{HAs} + \mathbf{A}^H\mathbf{H}^H\mathbf{n} = \mathbf{D}^H\mathbf{DAs} + \mathbf{D}^H\mathbf{V}^H\mathbf{H}^H\mathbf{n}$.

As shown in FIG. 2, at the first device 100, blocks of bits from a bit stream {b} are mapped onto a vector **s** with a mapping technique. The mapping technique may optionally include coded modulation to improve link margin. The bit stream {b} may be a file or collection of bits, representing any type of data, such as voice, video, audio, computer data, etc., that is divided or otherwise separated into discrete frames or blocks (generally referred to as signals) to be spatially multiplexed and simultaneously transmitted. One example is the simultaneous transmission of multiple IEEE 802.11x frames (each s_i may be a different frame) from the first device 100 to the second device 200, where, for example, the first device 100 is an IEEE 802.11 access point (AP) and the second device is a client station (STA). The product of the transmit matrix **A** and the vector **s** is a vector **x**. This matrix multiplication step effectively weights each element of the vector **s** across each of the N antennas, thereby distributing the plurality of signals among the plurality of antennas for simultaneous transmission. Components x_1 through x_N of the vector **x** resulting from the matrix multiplication block are then coupled to a corresponding antenna of the first communication device. For example, component x_1 is the sum of all of the weighted elements of the vector **s** for antenna 1, component x_2 is the sum of all of the weighted elements of the vector **s** for antenna 2, etc.

The transmit matrix **A** is a complex matrix comprised of transmit weights $w_{T,ij}$, for i = 1 to L and j = 1 to N. Each antenna weight may depend on frequency to account for a frequency-dependent channel **H**. For example, for a multi-carrier modulation system, such as an orthogonal frequency division multiplexed (OFDM) system, there is a matrix **A** for each sub-carrier frequency k. In other words, each transmit weight $w_{T,ij}$ is a function of sub-carrier frequency k. For a time-domain (single-carrier) modulation system, each transmit weight $w_{T,ij}$ may be a tapped-delay line filter.

Prior approaches involve selecting the weights d_p to maximize capacity

$$C = \sum_{p=1}^{L} \log(1 + SNR_p), \quad SNR_p = |d_p|^2 \lambda_p \frac{E(|s_p|^2)}{E(|n_p|^2)}$$

subject to a *total* power constraint emitted by the plurality of transmit antennas combined on the transmit matrix **A**, i.e.,

$$P_{TOT} = \mathrm{Tr}(\mathbf{AA}^H)\cdot\mathbf{E}|s_p|^2 = \mathrm{Tr}(\mathbf{VDD}^H\mathbf{V}^H)\cdot\mathbf{E}|s_p|^2$$
$$= \mathrm{Tr}(\mathbf{VDD}^H\mathbf{V}^H) < P_{max} \text{ (assuming } \mathbf{E}|s_p|^2 = 1)$$

The optimum solution to this problem is to use waterfilling to select the weights d_p (i.e., use waterfilling to put more power in eigenchannels with higher SNR λ_p).

The waterfilling approach requires N full-power capable power amplifiers at the transmitting device since, for some channels, it is possible for the optimal solution to require all or nearly all the transmit power to be sent from one antenna path. To reiterate, the prior approaches constrain the total power emitted from all of the antenna paths combined, simply $\Sigma P_i = P_{TOT} < P_{max}$ (for i = 1 to N antennas) where P_{max} is a total power constraint and P_i is the power from transmit antenna path i.

A better approach is to use a power constraint for each individual transmit antenna path. One such constraint is that the power transmitted from each antenna is less than the total power transmitted from all N antennas combined (P_{max}) divided by N, e.g., $P_i \leq P_{max}/N$ for all i. Using this approach, referred to as the "antenna power constraint" approach, each power amplifier can be designed to output (no more than) P_{max}/N average power, where P_{max} is the maximum power of the transmission from all of the N antennas combined. A significant benefit of this approach is that the power amplifiers can be designed to have lower maximum output power capability, thus requiring less silicon area. The use of smaller and lower-output power amplifiers has the benefit of lower on-chip power amplifier interference and lower DC current drain.

Using a P_{max}/N power constraint for *each* antenna, the problem becomes:

Maximize capacity C subject to

$(\mathbf{AA}^H)_{ii} < P_{max}/N$, i = 1,...,N.

This is a difficult problem to solve for d_p, since it involves finding the roots of a non-linear function using N Lagrange multipliers (one for each of the above N constraints). However, there is a simple non-optimal solution for each of two cases.

Case 1: $N \leq M$:

In this case, the transmitting device (having N plurality of antennas) multiplies the vector **s** representing the L signals $[s_1 \ldots s_L]^T$ to be transmitted with the transmit matrix **A** (i.e., computes **As**), where the transmit matrix **A** is computed with **D** set equal to $\mathbf{I} \cdot \mathrm{sqrt}(P_{max}/N)$ (where **I** is the identity matrix) enforcing equal power in each mode. As a result, $\mathbf{H}^H\mathbf{H}$ is Hermitian and (with probability 1) is full-rank, which means that **V** is orthonormal. Consequently, $(\mathbf{AA}^H)_{ii} = (\mathbf{VDD}^H\mathbf{V}^H)_{ii} = (\mathbf{VV}^H)_{ii}P_{max}/N = P_{max}/N$, which means that equal power P_{max}/N is transmitted at each antenna by a corresponding power amplifier of device 100, and the total transmit power is equal to P_{max}.

Case 2: $N > M$:

In this case, $\mathbf{H}^H\mathbf{H}$ is not full-rank. Let $\mathbf{v}_1,\ldots,\mathbf{v}_L$ denote the L eigenvectors for $\mathbf{H}^H\mathbf{H}$ having nonzero eigenvalues. Let $\mathbf{V} = [\mathbf{v}_1 \ldots \mathbf{v}_L]$, and let $\mathbf{D} = \mathrm{sqrt}(d \cdot P_{max}/N) \cdot \mathbf{I}$, where the power for each mode is the same and $d_p = d$ for p = 1 to L. The power in antenna path i is given by $(d \cdot P_{max}/N) \cdot (\mathbf{VV}^H)_{ii}$. Thus, the power emitted from each of the i antenna paths may be different. The transmitting device (having the N antennas) multiplies the vector **s** representing the L signals $[s_1 \ldots s_L]^T$ to be transmitted with the transmit matrix **A** (i.e., computes **As**), where the transmit matrix **A** is computed with **D** set equal to $\mathrm{sqrt}(d \cdot P_{max}/N) \cdot \mathbf{I}$, where the power for each mode is the same and $d_p = d$ for p = 1 to L.

Approach 1: Set $d = 1/z$, where $z = \max_i\{(\mathbf{VV}^H)_{ii}\}$. Then the maximum power from any antenna path is P_{max}/N. The total power from all antenna paths can be shown to be at least P_{max}/M and no greater than P_{max}.

Approach 2: Set d = 1. In this case, the total power emitted by the N plurality of antennas is P_{max}/M and the power emitted by antenna i for i = 1 to N is $(P_{max}/N) \cdot (\mathbf{VV}^H)_{ii}$.

Assuming the power amplifiers at devices on both sides of the link have the same peak output power, then for Case 1 and Case 2/Approach 2, the total power transmitted from the N antenna device will be equal to the total power transmitted from the M antenna device. Hence, the link between the two devices is symmetric in these situations. Case 2/Approach 1 is slightly more complicated (since it requires a normalization step) but has more transmitted power than Approach 2.

The solutions described above are capable of performing within 1 dB of the Shannon limit for a symmetric system (same number of antennas on both sides of the link), but facilitate use of smaller and more efficient power amplifiers in the radio transceiver, and as a result, achieve lower on-chip interference between radio paths (caused by the power amplifiers) than the waterfilling solution.

The antenna power constraint need not be the same for each of the transmit antennas and may be specific to or different for each antenna. Moreover, even if a different antenna power constraint is used for each antenna, each of the antenna-specific power constraints may be less than or equal to P_{max}/N.

The device 200 with M plurality of antennas will transmit to device 100 subject to the same type of power constraint at each of the M plurality of antennas. The cases described above are applied where M is compared relative to N, and the appropriate solution is used for transmitting signals to device 100.

FIG. 3 shows a block diagram of a radio communication device suitable for devices 100 and 200. Device 100 comprises a modem 120, a plurality of digital-to-analog converters (DACs) 130, a plurality of analog-to-digital converters (ADCs) 140, a MIMO radio transceiver 150 coupled to antennas 110(1) to 110(N) and a control processor 160. The modem 120, also referred to as a baseband signal processor, performs the baseband modulation of signals to be transmitted (vector **s**) and the baseband demodulation of received signals. In so doing, the modem 120 multiplies the vector **s** representing the L signals $[s_1 \dots s_L]^T$ to be transmitted by the transmit matrix **A**. The DACs 130 are complex DACs that convert the digital baseband modulated signals representing **As** to corresponding analog signals coupled to transmit paths in the MIMO radio transceiver 150. The ADCs 140 convert the received analog signals from corresponding receive paths in the MIMO radio transceiver 150 to digital signals for baseband demodulation by the modem 120. In the baseband demodulation process, the modem 120 will apply appropriate receive weights to the received signals to recover the L signals $[s_1 \dots s_L]^T$. The MIMO radio transceiver 150 comprises a plurality of radio transceivers each comprising a transmitter 152(i) and a receiver 154(i) associated with and coupled to a corresponding antenna by a corresponding switch 156(i). Each transmitter includes a power amplifier (not shown). The MIMO radio transceiver 150

may be a single integrated circuit or two or more separate integrated circuits. An example of a single-integrated MIMO radio transceiver is disclosed in co-pending and commonly assigned U.S. Patent Application No. 10/065,388, filed October 11, 2002, the entirety of which is incorporated herein by reference.

There are many ways to implement the modem 120. FIGs. 4 and 5 show block diagrams of examples of the transmitter section 120A and receiver sections 120B, respectively, of the modem 120, for a multi-carrier, e.g., orthogonal frequency division multiplexed (OFDM) application. Generally, matrix multiplication of the type described above is performed independently on each OFDM subcarrier to optimize performance for indoor frequency-selective fading channels. With reference to FIG. 4, the transmitter section 120A of the modem comprises a scrambler block 310, a block 315 of convolutional encoders, a block 320 of interleavers, a spatial multiplexer block 325 that performs the matrix multiplication with the transmit matrix **A** that is different at each of the OFDM sub-carriers k (i.e., $\mathbf{A} = \mathbf{A}(k)$), a subcarrier modulator 330, a block 335 of inverse Fast Fourier Transforms (IFFTs) and a block 340 of low pass filters. The output of the low pass filters block 340 is coupled to the DACs 130 (FIG. 3). A preamble generator 350 is also provided and is coupled to the DACs 130. As shown in FIG. 4, assuming the modem is in an N antenna device, there are L instances of blocks 315, 320 and 325 to perform processing on each baseband transmit signal stream and N instances of blocks 335, 340 and 130 for processing signals associated with each transmit antenna path..

The receiver section 120B shown in FIG. 5 comprises a block 415 of resamplers, a block of lowpass filters 420, a block 425 of numerically controlled oscillators (NCOs), a block 430 of FFTs, a block of equalizers 435 in which the receive weights are applied to the receive signals, a block of de-interleavers 440 and a block of convolutional decoders 445. A preamble processing and automatic gain control (AGC) block 450 and a channel estimator block 455 are also provided for channel estimation computations and other functions. The preamble and AGC block 450 recovers a preamble in the received signal and the channel estimator 455 generates knowledge about the channel **H**, which knowledge is supplied to the equalizer 435 to compute and apply receive weights to the signals output by the FFT block 430. Assuming the modem is in an N antenna device,

there are N instances of blocks 415, 420, 425 and 430 to perform processing on each received signal stream and L instances of blocks 435, 440 and 445 to recover the L signals.

As suggested in the description above of FIGs. 4 and 5, a first device passes channel response information to a second device by sending a known OFDM training sequence once through each antenna in, for example, a packet preamble. For a frequency domain implementation, the second device performs a space-frequency decomposition (SFD) given this channel information, and uses the SFD data to process received signals from that device, and to transmit signals back to the other device. This assumes reciprocity in the link, and therefore MIMO phase calibration at each device needs to be performed. Techniques for MIMO phase calibration are disclosed in commonly assigned and co-pending U.S. Patent Application No. 10/457,293, filed June 9, 2003, the entirety of which is incorporated herein by reference. Information regarding constellation order as a function of subcarrier index and eigenchannel may also be included in preamble. Each subcarrier has an associated constellation order for each eigenchannel. In the transmitter section 120A, a multi-dimensional vector trellis encoder (VTE) may be used to map input bits from the scrambler onto OFDM constellation symbols. Examples of multi-dimensional VTE's are known in the art. Other techniques for obtaining channel state information are known in the art as suggested above.

A modem may be built that applies the power constraint principles described above to a time-domain system implementation where tapped delay-line filters are used.

FIG. 6 illustrates how the more efficient antenna power constraint described herein compares to the optimal waterfilling approach.

In sum, a system and method are provided for MIMO radio communication between a first device having N plurality of antennas and a second device having M plurality of antennas. At the first device, a vector **s** representing L signals $[s_1 \ldots s_L]$ to be transmitted is processed with a transmit matrix **A** to maximize capacity of the channel between the first device and the second device subject to a power constraint that the power emitted by each of the N antennas is less than a maximum power, whereby the transmit matrix **A** distributes the L signals $[s_1 \ldots s_L]$ among the N plurality of antennas for simultaneous transmission to the second device. Similarly, a radio communication device

is provided comprising N plurality of antennas, N plurality of radio transmitters each coupled to a corresponding one of the plurality of antennas, and a baseband signal processor coupled to the N plurality of radio transmitters to process a vector **s** representing L signals [s_1 ... s_L] to be transmitted with a transmit matrix **A** to maximize capacity of the channel between the first device and the second device subject to a power constraint that the power emitted by each of the N antennas is less than a maximum power, whereby the transmit matrix **A** distributes the L signals [s_1 ... s_L] for simultaneous transmission to the second device by the N plurality of antennas. The transmit matrix **A** is computed subject to the power constraint being different for one or more of the N antennas or being the same for each of the N plurality of antennas. For example, in the latter case, the transmit matrix **A** may be computed subject to the power constraint for each of the N plurality of antennas being equal to a total maximum power emitted by all of the N plurality of antennas combined divided by N.

The above description is intended by way of example only.